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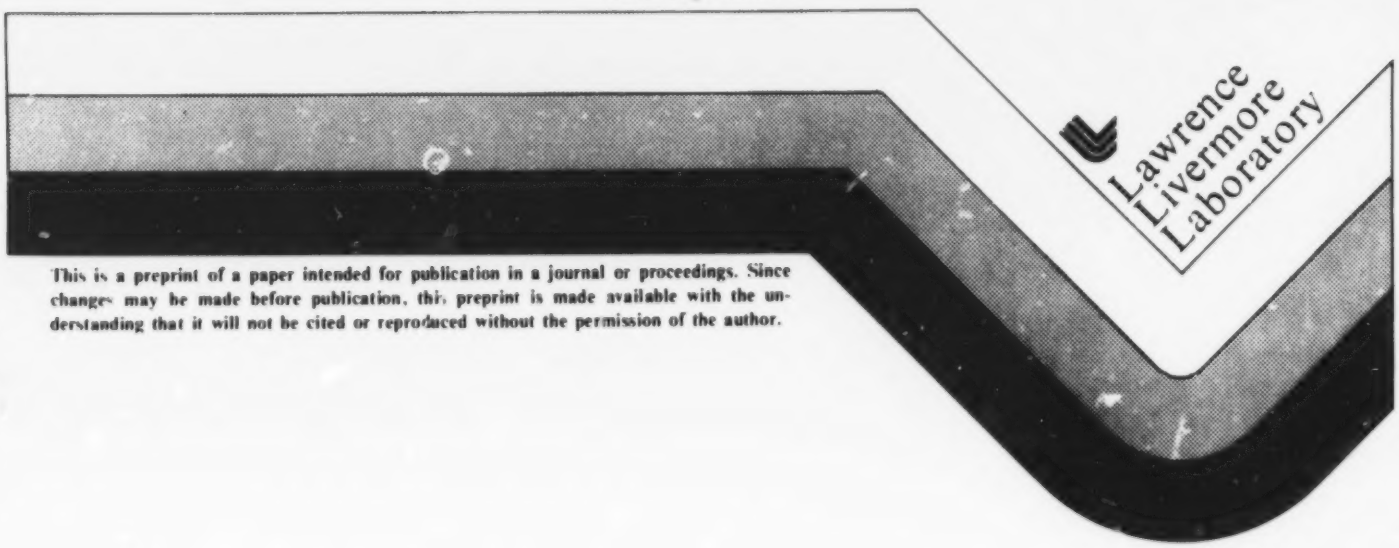

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GEOTHERMAL POWER PRODUCTION: IMPACT ASSESSMENTS AND ENVIRONMENTAL MONITORING

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David Layton is an environmental scientist at LLL specializing in the assessment of energy systems. In recent years he has been studying the environmental consequences of geothermal energy production. Kenneth Pimentel is a mechanical engineer who is interested in environmental monitoring and sampling. He was responsible for the implementation of a water quality monitoring program designed to acquire baseline data prior to geothermal development in the Imperial Valley of California.

ABSTRACT

This paper focuses on the role that baseline and postoperational environmental monitoring plays in assessing impacts of geothermal power production. Based on our experience in the Imperial Valley, where substantial geothermal resources exist, we examine the important characteristics of monitoring programs involving subsidence, seismicity, and air and water quality. We discuss the importance of environmental monitoring for situations where predictive models either do not exist (e.g., seismicity), or are still being developed (e.g., land subsidence). In these cases we emphasize the need for acquiring and analyzing data that can provide timely information on changes caused by geothermal operations. Monitoring is also useful in verifying predictions of air quality changes -- in particular, violations of ambient standards after control technologies are implemented. Water quality can be monitored with existing sampling programs where the potential for geothermal impacts is thought to be rather small. We summarize the significant issues in these environmental areas, the status of baseline data and predictive capability that currently exists, and the need for future monitoring and modeling programs to assess the impacts of geothermal development.

INTRODUCTION

The water-dominated geothermal resources of the western United States represent an important source of energy. For resources greater than 150°C, the total energy potential is estimated to be the equivalent of about 20,000 MW generated for 30 years (Muffler, 1979). Approximately a third of those resources are situated in California's Imperial Valley. To produce electricity from the valley's geothermal resources, hot fluids must be extracted from a geothermal reservoir, processed on the surface in a conversion facility, and then disposed. A 50-MW power plant using resources of 300°C would require approximately 1.5×10^6 kg of fluids each hour from a well field. Pipelines carrying fluids to the plant would probably be less than 2-km long to minimize excessive heat losses during transmission. As a result, the environmental consequences of geothermal energy production are largely restricted to the areas where the resources are located.

Two conversion processes are under development to produce electricity from geothermal fluids: flashed-steam and binary fluid. In the simple flashed-steam method, as shown in Fig. 1a, steam is separated from a liquid-steam mixture as it comes from a production well or well field and is then sent to a turbo-generator. Steam exhausted from the turbine is condensed, and the resulting condensate becomes a source of cooling water for the facility. Noncondensible gases present with the steam are either vented to the atmosphere or sent to abatement equipment to remove H_2S. With a binary process (see Fig. 1b), downhole pumps in production wells lift geothermal fluids to the surface where they are sent under pressure to a power plant. Heat exchangers at the plant transfer the thermal energy of the geothermal fluids to a binary fluid, which is vaporized and expanded through a turbogenerator. Binary-fluid vapor exhausted from the turbine is condensed, and recirculated through the heat exchangers. Noncondensible gases are not released

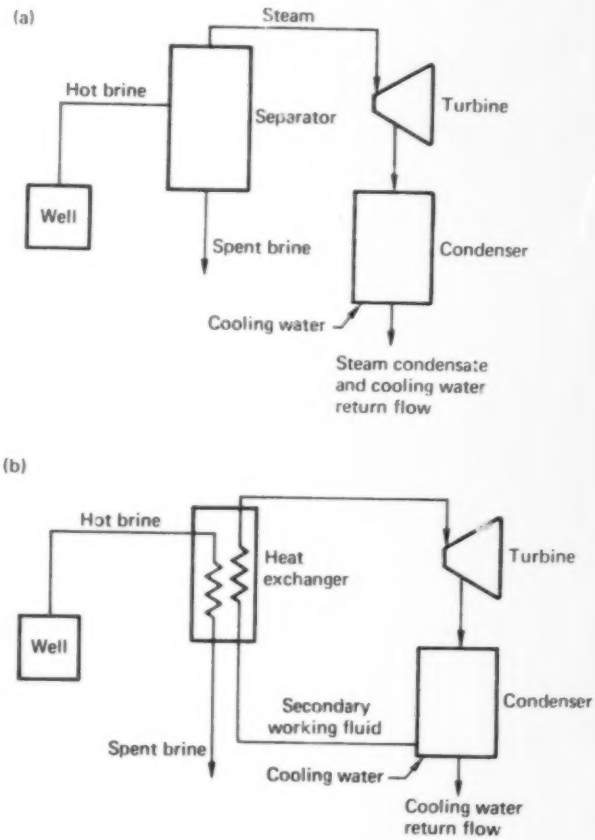

Fig. 1. Simplified geothermal conversion cycles for the (a) flashed-steam and (b) binary processes. Flashed-steam facilities emit noncondensible gases, but binary plants do not because fluids are kept under pressure and injected.

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to the environment with this process because geothermal fluids are not flashed to produce steam. But without the production of steam, condensate is not available for power plant cooling.

The success of such facilities will depend in part on whether they can be operated in an environmentally acceptable manner. Geothermal operations will also have to be compatible with irrigated agriculture, the dominant land use of the valley. For these to be achieved, potential impacts involving land subsidence, enhanced seismicity, air quality degradation, water pollution, etc. must be carefully assessed. And if adverse impacts are predicted, hopefully control technologies or mitigation measures can be implemented to avoid them. Unfortunately, the production of electricity from hot-water resources is an emerging technology, and as a result, there have been few opportunities to apply and validate methods and models to assess impacts. This has some serious implications. For example, inaccurate predictions of impacts caused by modeling errors could lead to adverse, unexpected impacts. These impacts could be costly to control, especially if control technologies have to be retrofited or if the operation of a generating facility has to be substantially modified.

IMPACT ASSESSMENTS AND MONITORING

Before the environmental consequences of a geothermal facility can be assessed, baseline environmental conditions must be measured and analyzed. Without this type of information, it would be difficult to determine what effects geothermal operations might have on the environment. The need for baseline data has been recognized by state and federal agencies involved with geothermal resources. The U.S. Department of the Interior, for example, has prepared a set of guidelines for acquiring baseline environmental data on federal geothermal leases for one year before energy production begins (U.S. Dept. of the Interior, 1977). The sampling and analysis of geothermal fluids must also be viewed as important parts of a monitoring program. At the present time, though, standards for the sampling and analysis of geothermal fluids have not been formally adopted (Vetter, 1979) and until they are established, assessment activities will be hampered by unreliable, inconsistent data on the chemistry of resources. Another requirement for an assessment is a characterization of the proposed conversion technology, including information on geothermal fluid requirements as well as the production of liquid, gaseous, and solid wastes.

To verify predicted impacts, or to detect impacts as they occur, it is necessary to obtain data from comprehensive baseline and postoperational monitoring programs. Those data must include measurements of environmental conditions, geothermal fluid chemistry, emissions of noncondensible gases, and other environmental residuals (e.g., accidental spills, emissions of cooling tower drift, etc.). Lawrence Livermore Laboratory recently completed the Imperial Valley Environmental Project (IVEP) for the Department of Energy. The purpose of the IVEP was to document baseline environmental conditions that existed in the valley prior to geothermal development, and to assess the impacts that large-scale geothermal power development might have on its regional environment. The project included regional studies and site-specific studies in the four major geothermal resource areas in the central part of the valley; emphasis was placed on environmental concerns near the large geothermal resources at the south end of Salton Sea (see Fig. 2). The following sections focus on the role that monitoring has in the assessment of impacts involving subsidence, seismicity, air quality, and water quality from our experience in Imperial Valley.

SUBSIDENCE

The removal of large volumes of hot water from a geothermal reservoir will decrease its pore pressure, resulting in compaction of the aquifer or aquifers forming the reservoir. The degree of compaction will depend on the physical properties of the aquifer materials. As subsurface compaction increases with declining reservoir pressures, some of the compaction could be expressed as a depression in the land surface. Such a depression in the Imperial Valley could directly hinder the irrigation of lands that are carefully graded to facilitate the application of water to crops. The valley is already subsiding naturally, and measurements of land elevations made periodically since 1971 indicate that subsidence is occurring at rates as high as 4 cm/yr (Reese, 1977). Natural subsidence is regionally distributed, and is not known to have caused damage.

In order to assess the impacts of land subsidence, changes in the elevation and slope of the land surface above a compacting reservoir must be estimated. However, models of subsurface compaction and related subsidence associated with geothermal fluid extraction have not been fully verified (Atherton et al., 1976). As a consequence, their usefulness as an assessment tool is limited. On the other hand, surface measurements of land elevation may not provide an early indication of the possible extent of surface deformation. Furthermore, surface measurements alone do not provide the kinds of information needed to verify models of subsurface compaction and surface subsidence. A more important parameter to measure is the compaction taking place in the reservoir. Measurements of compaction would provide information on the response of the reservoir materials to actual pressure declines. Estimates of compaction could be obtained by measuring changes in the distances between casing collars in a production well (Brandt, 1978). Field data on compaction could be used to check the accuracy of laboratory measurements of the compaction of reservoir materials under simulated in-situ conditions (Schatz et al., 1979). If laboratory data on compaction are shown to be accurate, then these data can be used to improve the prediction of deformation within a reservoir. Better information on deformation in the reservoir and in overburden could lead to better estimates of changes in surface elevation. As a consequence, improved assessments of potential impacts to irrigated lands can be made.

INDUCED SEISMICITY

The preferred disposal method for spent geothermal fluids is subsurface injection. It may also be required as a means of controlling land subsidence. There have been concerns, though, that fluid injection could induce seismic activity, based on experience in Colorado and elsewhere in which the high-pressure injection of fluids triggered earthquakes (Raleigh et al., 1975). Injection of residual fluids from geothermal operations will not be done at high pressures, so it does not appear likely that induced seismicity will occur. Nevertheless, the possibility of increased seismicity resulting from injection cannot be entirely ruled out. The Imperial Valley is one of the most seismically active areas in the United States. An earthquake of moderate magnitude (6.6 Richter) on October 15, 1979 caused damages estimated at $30,000,000 in the valley (Real et al., 1979). Because of this high level of natural seismicity, monitoring will be necessary in order to determine whether seismic patterns change with injection activities (Crow and Kasameyer, 1978). Fortunately, there is a set of seismographic stations in the valley to monitor earthquakes. Data on the location and depth of earthquakes obtained from these stations will form the basis for subsequent comparisons of seismic activity occurring before and after geothermal facilities are installed.

AIR QUALITY

The emission of H_2S has been identified as the principal environmental problem associated with geothermal development at The Geysers, a vapor-dominated resource in northern California (Ermak and Phelps, 1978). The cumulative emissions from over 500 MW of development have resulted in ambient concentrations of H_2S that exceed California's 1-h standard of 30 ppbv (Rosen and Molenkamp, 1978). Now generating facilities at The Geysers are being equipped with control technologies to abate H_2S. Will geothermal development in the Imperial Valley encounter similar air quality problems?

To address that question, an air quality monitoring and assessment program was conducted as part of the IVEP. Baseline air-quality data were collected at six monitoring stations in the valley. An analysis of the data showed that ambient concentrations of H_2S were generally below 10 ppbv. However, some of the daily maximum values did exceed the California air quality standard (Gudiksen et al., 1979). A possible explanation for excursions above the standard is the use of liquid-sulfur fertilizers in irrigation water that release H_2S into the atmosphere. Ambient concentrations of ozone were found to be higher than expected for a rural area. Other pollutants, such as SO_2, NO, and NO_x, were found to be at low levels.

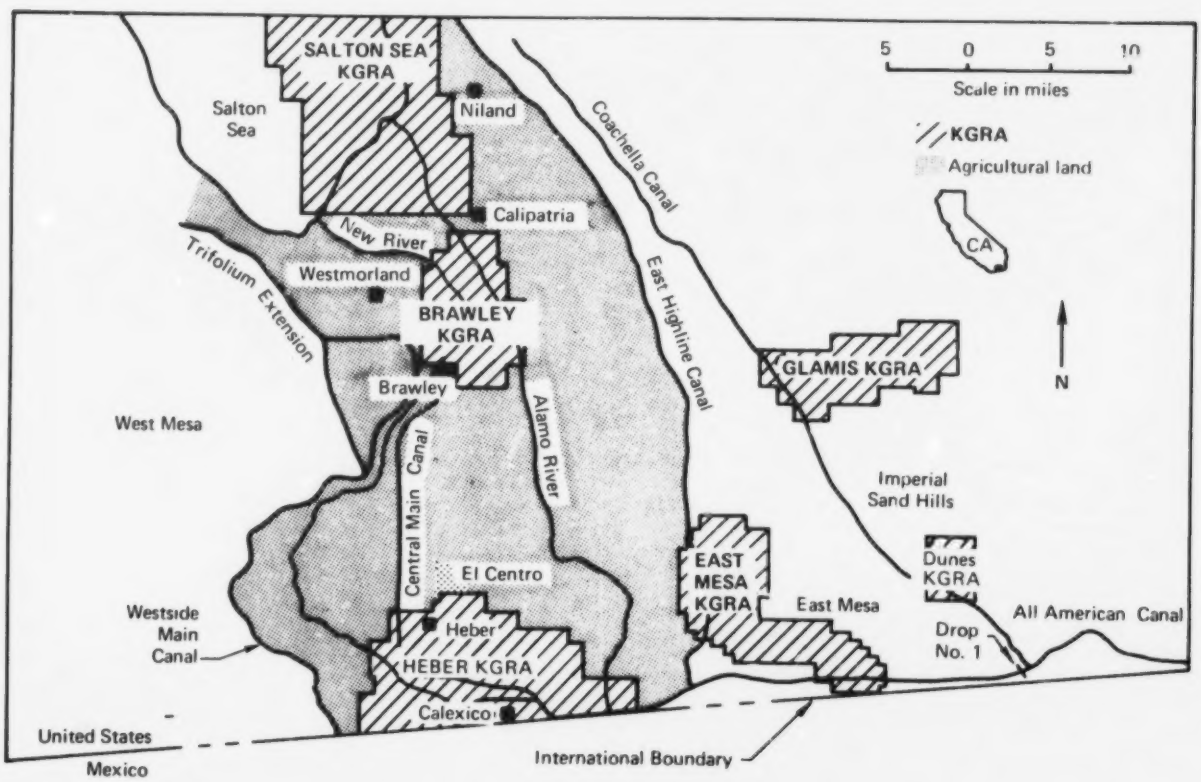

Fig. 2. Imperial Valley, California and its Known Geothermal Resource Areas (KGRAs). One-third of all the hot-water geothermal resources in the western United States are situated in this region.

Atmospheric stability, wind velocities, and inversion heights were also measured at the stations. These parameters were monitored for use in atmospheric transport modeling. The concentrations of H_2S, NH_3, CO_2, CH_4, Hg, and Rn in the steam phase of geothermal fluids were measured in order to calculate estimated emission rates from future power plants.

A three-dimensional, particle-in-cell atmospheric transport model was used along with a steady-state Gaussian plume model to simulate the air quality changes associated with a 3000-MW scenario of future energy production. The scenario includes a siting pattern for 30 power plants distributed among the valley's four major geothermal resource areas. The simulations indicate that without abatement of H_2S, the California hourly standard of 30 ppbv would be exceeded at least 1% of the time over approximately a third of the valley (Ermak et al., 1979). Therefore, to attain this level of development control technologies will be necessary to reduce emissions of H_2S. Power plants in the Salton Sea and Brawley resource areas may have to reduce emissions by as much as 90% to prevent violations of the standard.

Postoperational monitoring will eventually be necessary to update the baseline measurements and to monitor changes in air quality after geothermal development takes place. Monitoring data will be used to determine whether control technologies for H_2S can achieve the abatement efficiencies needed to prevent violations of the California air quality standard. If necessary, these data can also be used to verify the predictions of air quality models that are updated to account for the introduction of new geothermal facilities.

WATER QUALITY

Water quality problems resulting from geothermal development vary with the resource type and conversion technology, as well as with local beneficial uses of water. Environmental research in both the Imperial Valley and Geysers areas of California has revealed that the sets of potential water quality issues in those areas differ considerably (Pimentel et al., 1978; Pimentel, 1978). The availability of baseline and postoperational environmental data is also quite different in these two regions. It follows, then, that monitoring and impact assessment methods should be tailored to these differing sets of concerns.

Beneficial uses of water in the Imperial Valley include agricultural, municipal, domestic, and industrial water supply, and aquatic habitat. The geothermal fluids in the valley contain dissolved solids contents that range from less than 2,000 mg/l to more than 300,000 mg/l. Elevated concentrations of substances that can be toxic for all these beneficial uses have been found in the fluids; among these are As, B, Ba, Fe, Li, Mn, Pb, Se and Zn. High levels of salts and toxic chemicals in the fluids could pose significant threats to those beneficial uses.

The water quality study of the IVEP established a detailed baseline of 30 water-quality parameters at 75 sites in the valley where monthly samples were collected from fall 1976 through winter 1978. That data base contains analyses for the following lists of major and trace chemical constituents and physical parameters (Pimentel, 1980):

- Na, K, Ca, Mg, Cl, SO_4, CO_3, HCO_3, SiO_2, TDS, SC, pH, Temp.;
- Ag, As, B, Ba, Cd, Cr, Cs, Cu, F, Fe, Hg, Li, Mn, Mo, Ni, Pb, Rb, Se, Sr, V, Zn.

These data show that water quality is quite poor to begin with in Imperial Valley. The major consumptive use for water in the valley is agricultural irrigation. Imported Colorado River water is used for irrigation and contains 900 mg/l of dissolved salts on the average. This high-salinity water has made it necessary to grow only salt-tolerant crop species in areas of the valley with heavy soils where leaching is poor. The same imported river water is used to supply area municipal water treatment plants.

Levels of dissolved solids and sulfate in this water exceed the recommended limits of the U.S. Public Health Service for drinking water. Aquatic species that inhabit the agricultural canals and drains, the rivers, and Salton Sea have accommodated themselves to the high salinity, hardness, and temperature of the valley's water. Additional stress is imposed on aquatic organisms by pesticide residues that remain from agriculture.

Potential effects of geothermal development in Imperial Valley vary somewhat over the different geothermal resource areas of the valley. Hypersaline brines in areas near the Salton Sea could present major problems to agriculture and aquatic habitat should accidental spills occur at future power plants. Reclamation of affected cropland in that area could be difficult and costly in the event of a massive spill of geothermal brine (Tompkins et al., 1980). Effects on any given surface water channel could be severe, though localized and transient. This type of problem is less severe moving southward across the valley because dissolved-solids levels of geothermal fluids generally decrease in that direction. Geothermal resources in the East Mesa area differ from those in the rest of the valley. Many of the production wells drilled thus far in the East Mesa average no more than 2,000 mg/l in dissolved salts; however, many have elevated levels of trace elements that are toxic to agriculture, including B, F, Li, Mn, and Se. But most of the area is undeveloped desert land so that the potential effects of spills are far less severe than in the agricultural portions of the valley. A potential concern in the eastern portion of the valley is contamination of shallow groundwater resources. Domestic water wells are in use down-gradient from the existing geothermal operations in East Mesa. They also exist just east of the geothermal development near Brawley. If geothermal well-drilling and completion operations are not carried out properly, underground leaks might occur that could threaten the quality of the domestic groundwater resources in these areas.

While significant baseline data may exist for the valley, it is difficult to predict impacts geothermal operations may have on water quality. The California Regional Water Quality Control Board

requires injection of spent geothermal fluids in the valley and prohibits disposal to surface-water channels. The only likely effects to water quality under these conditions will be possible leaks in the underground production or injection wells that could affect groundwater quality, as mentioned above, and effects due to accidental spills. To build detailed models of surface-water quality for a region like the valley, with its thousands of miles of agricultural canals and drains, would be a prohibitive task in order to study the regional effects of intermittent accidental spills. However, localized effects could be studied by postulating a spill into some surface-water channel if detailed chemistry is available for the geothermal fluid and the receiving water. In such a case, a chemical equilibria program like GEOCHEM (Sposito and Mattigod, 1979) can be used to investigate mobility, availability, and speciation of toxic trace substances (Ireland, 1980). Models of subsurface hydrology exist for many types of aquifer studies (Pimentel, 1977). However, transport models require substantial data on subsurface structure and geochemistry. To our knowledge, sufficient data does not exist today to study the effects of possible geothermal well leaks on domestic groundwater resources in the valley. Without large amounts of data on stratigraphy and aquifer interconnection in this alluvial valley, results of such modeling studies would be highly suspect. Thus, for both surface water and groundwater, we believe future study of water-quality effects of geothermal development should emphasize ongoing monitoring rather than predictive modeling.

We have recommended that a reduced network of sampling sites be monitored on a continuing basis in the valley as geothermal development proceeds (Anspaugh et al., 1978). Our baseline study allowed us to identify a minimum set of water chemicals that would provide cost-effective information to use to detect trends in water quality that may be caused by geothermal facilities (Pimentel et al., 1978). Furthermore, we recently completed a network of seven shallow groundwater witness wells in the valley to monitor changes in shallow groundwater chemistry. The U.S. Geological Survey and California Regional Water Quality Control Board have initiated a cooperative agreement to carry out the monitoring program we recommended. Data from that program will prove useful in assessing the changes that may occur in water quality as geothermal energy production begins in the valley.

CONCLUSIONS

Land subsidence is perhaps the most important environmental concern to geothermal development in the Imperial Valley because it could adversely affect agricultural operations. Existing subsidence models are largely unverified. Adequate measurements to predict potential subsidence caused by geothermal fluid withdrawal do not exist. In our opinion, postoperational monitoring programs should be implemented to monitor both subsurface compaction and surface subsidence. These data can be used to provide an early warning of impending subsidence and to improve models of land deformation resulting from reservoir compaction. Seismographs have been installed in the valley to record earthquakes, but there is little or no capability to reliably predict future seismic events. The Imperial Valley is one of the areas of highest natural seismicity in this country. The potential for geothermal development to cause earthquakes in the Imperial Valley is very low; however, data from existing monitoring programs should still be analyzed to determine whether seismicity changes after geothermal development. Air quality models are developed to a relatively high degree of sophistication. A large baseline of air quality data exists for the valley. Emission of H_2S is one of the key concerns to geothermal development in the area, primarily because low concentrations of this gas can produce odor annoyances. For these reasons, we feel it important that ongoing monitoring programs be established to preserve the integrity of the existing baseline data, detect air quality trends, determine future abatement needs, and verify present and future predictive assessments. Although geothermal fluids could pose serious threats to water quality in Imperial Valley, subsurface injection of spent fluids will be required and that should eliminate most water quality impacts. The remaining potential impacts to water quality are of relatively low importance. A detailed water-quality baseline already exists in the valley. Inordinately large amounts of data would be required to implement water-quality models for this region. Therefore, we feel that the sampling programs now underway will be sufficient to detect significant changes in water quality that may be caused by geothermal energy production in Imperial Valley.

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